

Forest Environmental Investments and Implications for Climate Change Mitigation

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ABSTRACT

Forest environmental conditions are affected by climate change, but investments in forest environmental quality can be used as part of the climate change mitigation strategy. A key question involving the potential use of forests to store more carbon as part of climate change mitigation is the impact of forest investments on the timing and quantity of forest volumes that affect carbon storage. Using an economic optimization model, we project levels of U.S. forest volumes as indicators of carbon storage for a wide range of private forest investment scenarios. Results show that economic opportunities exist to further intensify timber management on some hectares and reduce the average timber rotation length such that the national volume of standing timber stocks could be reduced relative to projections reflecting historical trends. The national amount of timber volume is projected to increase over the next 50 yr, but then is projected to decline if private owners follow an economic optimization path, such as with more forest type conversions and shorter timber rotations. With perfect foresight, future forest investments can affect current timber harvest levels, with intertemporal linkages based on adjustments through markets. Forest investments that boost regenerated timber yields per hectare would act to enhance ecosystem services (e.g., forest carbon storage) if they are related to the rate of growth and extent of growing stock inventory.

CARBON as part of forests' environmental attributes is receiving increasing attention because of concerns about climate change and mitigation options. Forest ecosystems store about half of all terrestrial carbon (Intergovernmental Panel on Climate Change, 2000), and human activities significantly alter land use and forest cover and affect the circulation of carbon and its distribution in terrestrial ecosystems. Millions of forest and agricultural land owners in the United States and other countries are key players in how the world's land base is currently utilized and how it might be used to increase carbon sequestration and help address global climate change (GCC). For example, about two-thirds of carbon stored on U.S. timberland is on private lands, and these private lands offer substantial opportunities for more carbon storage (Birdsey et al., 2000). Given the long maturation periods for most forest species, substantial increments in carbon need to be planned well in advance of actual on the ground storage. At a national scale, we investigate a range of scenarios involving different levels of private and government investment in U.S. forests and attendant effects on timber stocks, with implications for carbon storage.

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Land use, land use change, and forestry have received increasing attention in GCC analyses over the last decade (e.g., Intergovernmental Panel on Climate Change, 2000). Experts in forestry, biology, ecology, economics, and related subjects have increasingly investigated human activities that alter land use and land cover. Factors that influence adaptation and the net terrestrial uptake of carbon include the direct effects of land use and land-use change (e.g., deforestation and agricultural abandonment and regrowth) and the response of terrestrial ecosystems to CO₂ fertilization, nutrient deposition, climatic variation, and disturbance (e.g., timber harvest, fires, wind-throws, and major droughts). Direct mitigation strategies include reducing carbon emissions from forests by reducing the conversion of forests to farmland and other uses (i.e., reducing deforestation), setting aside existing forests from harvest, and reducing biomass burning. Other land-based strategies for increasing carbon buildup in forests are converting marginal agricultural land to forests (carbon plantations, forest product plantations, short-rotation woody crops, or joint product plantations), and enhancing forest management (e.g., Hoen and Solberg, 1994). Research findings can inform decision-makers about GCC adaptation and mitigation possibilities, while recognizing dynamic interactions among climate, ecological, and socioeconomic systems and attendant effects on agriculture, forestry, and natural resources.

Our integrated approach to analyzing the potential role of forestry in climate change mitigation strategies recognizes the major factors of biophysical–ecological, economic, and social influences on land management and investment behavior. The interface between ecological and economic factors involves a human ecology portion that includes physical patterns observed on a landscape. The economics portion involves consideration of financial returns and consumer demands, with distinction between private and social viewpoints, in that some effects are external to private producers' and consumers' outcomes. Social aspects in recognition of market failures or externalities can include government programs that can subsidize forest production to promote increases in standing timber stocks and forest carbon storage. Next, we look at historical trends in U.S. forest conditions because macro trends typically are not quickly reversed or substantially altered and provide useful information when contemplating intervening in ecosystems, markets, and social processes. Then, we describe our modeling methods, summarize projections for different forest investment scenarios, and discuss find-

Abbreviations: EO, economic optimization; FASOM-GHG, Forest and Agricultural Sector Optimization Model-Green House Gas; GCC, global climate change; HB, historical behavior; MIC, management intensity class; NIPF, nonindustrial private forest.

ings and point out policy implications and examples of future research needs.

HISTORICAL TRENDS IN FOREST CONDITIONS

The size of the forestland base and its dynamics, the latter influenced by ownership, play critical roles in determining the quantity and quality of outputs from the forests, such as the amount of stored forest carbon. Accurate evaluation of prospective forest policies requires an understanding of the underlying patterns of forest growth, harvest, and investment, and estimates of a policy's impact on such forestry activities. Trees on U.S. timberland stored 11685 million Mg of forest carbon in 1992 (Birdsey and Heath, 1995), and with about 75% of U.S. timberland privately owned, the responses of private owners to investment incentives are important considerations for policymakers.

In the 1800s and early 1900s, deforestation was a source of CO₂ emissions in the United States. However, by the 1950s, U.S. forests had become a sink, absorbing more CO₂ through forest regrowth than was being lost through harvesting (Birdsey and Heath, 1995). With a projected U.S. population increase of more than 120 million people over the next 50 yr, more than 20 million ha of U.S. forest are projected to be developed (Alig et al., 2004). The United States would have less timberland area to support tree growth to sequester and store additional carbon, with a *net* reduction of about 6 million ha of timberland by 2050 (Alig et al., 2003).

To counter effects of deforestation, afforestation as a climate change mitigation option can potentially provide the most additional carbon sequestration in the United States over the next 10 to 30 yr (Birdsey et al., 2000). Government policies have influenced afforestation amounts, with periodic spikes in the amount of U.S. tree planting correlating with major government programs (Alig et al., 1980), including a spike in the latter half of the 1980s due to subsidized tree planting for environmental goals (e.g., reduced soil erosion). In the absence of such programs, projections by Kline et al. (2002) based on historical relationships indicate that the amount of tree planting in the U.S. South by the large nonindustrial private forest (NIPF) ownership class could decline in the future without cost-sharing or other subsidies.

However, other tree planting in reforestation of harvested forestland can encourage establishment of fast-growing species to foster more carbon storage in woody biomass (Hair et al., 1996). On a smaller land base, industry tree planting is projected to rise gradually with more timber harvest (Kline et al., 2002).

In most years timber harvest is the disturbance having the greatest effect on U.S. timberland and can lead to significant changes in land cover and forest carbon storage, shifting some carbon from forest ecosystems to wood product storage. Private timber harvests comprise more than 90% of the U.S. total. Projections based on "historical behavior" (HB) indicate that both timber harvest levels and standing timber stocks can increase in the future (Fig. 1) (Haynes, 2003). Implications for forest

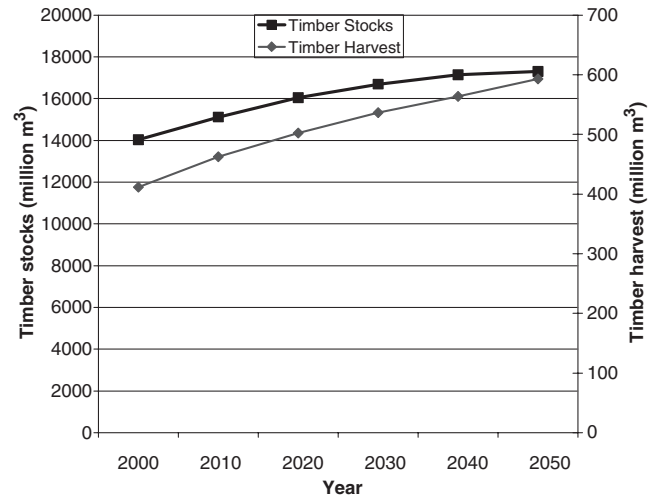


Fig. 1. Projected national inventory of private standing timber stocks and timber harvests in the coterminous United States: 2000–2050 (from Haynes, 2003).

carbon storage are possible increases in the future as well, as Birdsey and Heath (1995) estimated that U.S. forests will continue to be net carbon sinks well into the future, sequestering carbon at an average net annual rate of 178 million Mg between 1992 and 2040 (not including sequestration into wood products and landfills), for a total increase in stored forest carbon of 8.5 billion Mg. Earlier "economic optimization" (EO) projections of forest investment indicated that expanded private forest investment relative to a HB baseline would allow some immediate increments in timber harvest, sustained increases in timber inventory, and virtually no long-term trend in softwood log prices (Alig et al., 1999a).

Related information needed by GCC policymakers is updated information on both the likely level of forest volumes and forest carbon storage *if* private owners continue to invest in line with historical behavior, and *if* the economic potential of U.S. private timber production was attained. The latter EO case includes the possibility of more forest investment in the form of plantations and other intensified forest management. Potential of carbon sequestration in forest biomass through silvicultural management has been examined at the stand level (e.g., Hoen and Solberg, 1994) and at larger scales (e.g., Hair et al., 1996; Plantinga and Birdsey, 1993). However, the investment-related linkage among management of existing timber stocks, reforestation, and changing land use has not previously been modeled except in recent timber market models (Alig et al., 1998; Adams et al., 1999).

METHODS

To investigate the possible outcomes of EO forest investment, we used a linked model of the forest and agricultural sectors. The Forest and Agricultural Sector Optimization Model-Green House Gas version (FASOM-GHG), is a dynamic, nonlinear programming model of the forest and agricultural sectors in the United States (Adams et al., 1997; Alig et al., 1998; McCarl et al., 2005). The model simulates the allocation of land over

time to competing activities in the forest and agricultural sectors and the resultant consequences for the commodity markets supplied by these lands. (The carbon accounting in the FASOM-GHG model, as part of the greenhouse gas accounting, is still being tested, and so was not used in this study.) The model has been applied for more than a decade to evaluate the welfare and market impacts of public policies pertaining to GCC impacts and mitigation activities that can cause land transfers between the sectors and alterations of activities within the sectors. In this paper, we focus on the forest sector. For an example of a FASOM-related study providing insights into potential carbon storage in the agricultural sector, see Murray (2004).

FASOM models intertemporal optimizing behavior by economic agents. The decision to continue growing a timberland stand rather than harvesting it now is based on comparison of the net present value of timber harvests from future periods and any greenhouse gas offsets obtained (from not harvesting now) versus the net present value of harvesting now and either regenerating the land back to trees or shifting to agricultural use. Similarly, an afforestation decision would shift land out of agriculture if it had a greater net present value in forest use. This land-use optimization establishes a land price equilibrium across the two sectors and, given the land base interaction, a link between contemporaneous commodity prices in the two sectors as well.

The forest production component of FASOM-GHG depicts the use of existing private timberland as well as the reforestation decision on harvested land across the conterminous United States, broken into nine market regions (Fig. 2). Timberland is the subset of forestland that is capable of producing at least 0.23 m³ per ha per year of industrial wood at culmination of mean annual increment and is not withdrawn from timber harvesting or related timbering activities. Timberland is differentiated by region, the age cohort of trees (grouped in twenty-one 5-yr cohorts: 0 to 4 yr, 5 to 9 yr...up to 100+ yr; harvesting is assumed to occur at the midyear of the cohort), ownership class, cover type, site condition, management regime, and suitability of the land for agricultural use. Decisions pertaining to timber management invest-

ment are endogenous. Actions on the timber inventory are depicted in a framework that allows timberland owners to institute management activities that alter their inventory to maximize net present value of the economic returns from the activities. Decisions for existing stands include selecting the harvest age. Lands that are harvested and subsequently reforested or lands that are converted from agriculture to forestry (afforested) introduce decisions involving the choice of species type, management type, and future harvest age.

A key determinant of what timber volumes will grow in the various timberland strata of the forest inventory are current and possible future timber management regimes, referred to here as timber management intensity classes (MICs). The MICs describe methods of regeneration (natural or planted), stand density control (pre-commercial or commercial thinning), fertilization, and method of harvest (partial cutting or clearcutting). The number of MICs and species types in the current FASOM-GHG model (McCarl et al., 2005) were significantly expanded for the key timber supply regions of the South and Pacific Northwest Westside compared to the original FASOM model (Adams et al., 1997). For these key timber supply regions, we have multiple MICs, under management regimes representing even-aged and uneven-aged stands.

An important aspect of the MIC is the associated costs. Included in the FASOM-GHG model are conversion, establishment, and forest management costs for each specified MIC (Bair and Alig, 2006). Forest establishment costs include those for site preparation, tree seedlings, and tree planting. Intermediate timber management costs include those for precommercial thinning, prescribed burning, fertilization, and any other practices between stand establishment and harvest. Establishment costs vary by FASOM-GHG land class, with generally higher costs for reforested hectares than for afforested hectares.

To estimate the impact of biological and financial changes to timberland inventories and harvest levels, we modeled alternative policy scenarios that create incentives and disincentives for timberland investment. These scenarios include sensitivity analyses involving forest management costs and timber yields. Restriction and expansion of high intensity timberland management is also modeled in the FASOM-GHG scenarios.

Our first set of scenarios (Scenario Set A) involves changes in costs of forest establishment and forest management for both existing and regenerated stands, testing both 50% reductions (Scenario A1) and increases (Scenario A2) compared to the baseline. The reduction is in line with cost sharing as a policy that provides incentives for timberland investment. Most state and federal tree planting programs provide approximately 50% of the incurred cost of timberland establishment (Alig et al., 1990). This level of cost reduction is modeled and is held constant throughout the projection period. The assumption is made that timberland owners would take advantage of conservation easements, carbon credits, or technology assistance programs to reduce the intermediate and general management costs over the projection period by 50%. Conversely, we also increase

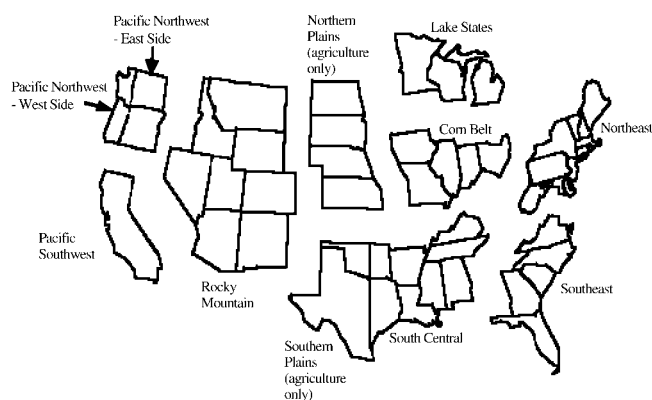


Fig. 2. Map of the nine timberland regions used in the Forest and Agricultural Sector Optimization Model-Green House Gas (FASOM-GHG) modeling system (McCarl et al., 2005).

timberland management costs by 50%. This increase in costs may occur if global climate change negatively influences precipitation and temperatures in timber producing regions, increasing the cost of establishment and management costs.

The next set of scenarios (Scenario Set B) involves changes in projected yield estimates for regenerated stands. Projected yield increases of 15% (Scenario B1) in FASOM-GHG compared to the baseline case represent the upper end of estimated gains from improved management and climate change favorable to timber production. Joyce and Nungesser (2000) state that improved management of timberland stands could increase yields 25 to 39%, while increased CO₂ levels may increase yields by another 8 to 29%. However, changes in temperature and climate may reduce timberland yield in various locations. Considerable uncertainty exists about the influence that climate change may have on forest growth rates (Alig, 2003). Gains from increased management intensity would primarily occur on NIPF timberlands in the South Central and Southeast regions (Alig et al., 1999a), but for consistency are applied to all private owner groups across regions. The decreased yield scenario is the opposite of that for the assumed yield increase, with a reduction in yields by 15% (Scenario B2).

The last set of scenarios (Scenario Set C) involves assumed changes in forest investment that reflect intensity of forest management. The first scenario involves assuming increased forest investment (Scenario C1) to counter the projected baseline reduction in timber inventory in the latter half of the projection period. This equates to timber yield increases of approximately 35% for regenerated stands in the future. This emulates a relatively optimistic boost in timber yields, to help bracket the set of sensitivity analyses. At the other extreme, our relatively pessimistic scenario regarding reduced future forest investment involves elimination of tree planting (Scenario C2) when regeneration opportunities arise in the future, so that only natural regeneration and associated timber yields were employed after a stand was harvested.

In each of the aforementioned scenarios, standing timber volume is used as one indicator of forest carbon storage potential. This allows us to compare on a standing timber volume basis with the “historical behavior” case described earlier from the recent national timber assessment (Haynes, 2003), where the latter did not report forest carbon estimates and projects out 50 yr compared to 100 yr in this study. Significant differences in carbon storage can exist across forest types (Birdsey, 1992), and our preliminary projections from the updated FASOM-GHG model represent more forest types than the earlier 1990s model (McCarl et al., 2005).

RESULTS AND DISCUSSION

In the EO baseline scenario projected by the FASOM-GHG model, the national amount of standing private timber volume increases 15% over the first half of the 100-yr projection period, less than the increase (23%) in the HB projection (Fig. 1). In the EO case, the

economic opportunity costs of holding timber beyond merchantable age exerts downward pressure on the amount of forest stock relative to the HB case. However, the 15% increase in the amount of EO standing timber stocks suggests that significantly more forest carbon storage is possible, along with increases in carbon stored in wood products, as average timber harvest amounts also increase by 2050, by 28%.

The EO baseline projections extend out to 2100, in contrast to 2050 for HB, and show a 16% reduction in timber stocks from 2050 to 2100. The amount of national timber stocks is reduced in the latter half of the projection as proportionately more timberland is moved into plantations and other intensified forms of forest management. This would represent a transition to, on average, timber stands that are harvested at earlier ages than historical ones and with less volume per hectare. By 2100, the EO transformation of private timber stands results in a terminal amount of standing stock volume about 4% lower than the starting inventory in 2000.

Across the EO scenarios where costs (Scenario Set A) or timber yields (Scenario Set B) were altered by assumption, the scenario with the 15% increase in timber yields (Scenario B1) had the largest increases in both halves of the projection period relative to the baseline (Table 1, Fig. 3). However, even that scenario had an absolute volume decrease in the second half of the projection period, as the model effectively concentrates timber production on a smaller timberland base. To attain a projected timber volume trajectory that did not decline, enough forest investment (Scenario C1, “Increased Investment”) would be needed to boost regenerated timber yields by approximately 35% (Table 1). Relative to the EO baseline, growing stock volume under the increased investment scenario (Scenario C1) moves notably upward after 2030 and by 2100 results in national timber stocks that are more than 25% larger than the base case (Fig. 3).

Altering costs for timber management and forest establishment (Scenario Set A) results in much smaller corresponding EO changes compared to the timber yield cases (Scenario Set B) (Table 1). We do not show the cost scenario results (Scenario Set A) in Fig. 3 because they

Table 1. Percentage changes in national private timber stocks 2000–2050 and 2050–2100 across scenarios, and changes in total harvest relative to economic optimization (EO) baseline.

Description (scenario)	Change in timber stock volume		Total harvest amount relative to EO baseline (=1)
	2000–2050	2050–2100	
	%		
Baseline	15	–16	–
Costs decreased 50% (A1)	16	–14	1.004
Costs increased 50% (A2)	13	–18	0.995
Yields increased 15% (B1)	20	–6	1.027
Yields decreased 15% (B2)	14	–22	0.980
Increased investment (C1)	22	3	1.058
Restricted investment (C2)	17	–29	0.842

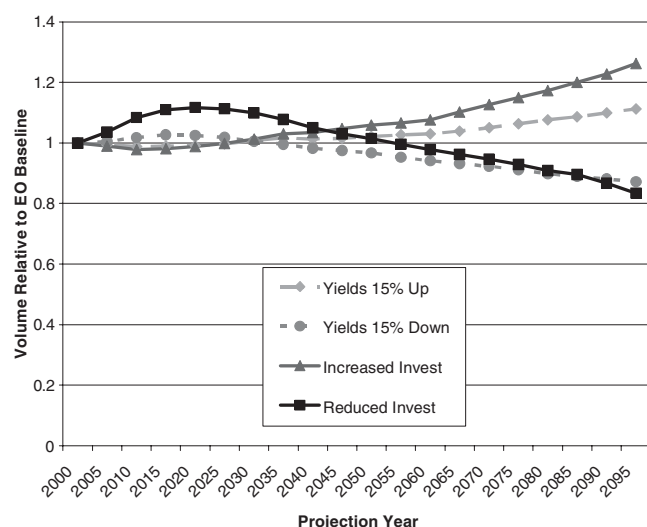


Fig. 3. Projected national stocks of private growing stock for timber yield and forest investment scenarios, relative to economic optimization (EO) baseline levels, in the coterminous United States: 2000–2100.

are bracketed by results from the other scenarios. If costs are increased 50% above the baseline levels (Scenario A2), the corresponding percentage change in the projected levels of ending point inventory is notably less. This reflects an inelastic response of the amount of standing timber volumes to cost estimates, with many hectares coming into solution under a wide range of forest establishment and timber management costs.

Intertemporal linkages between forest investment and timber harvest amounts, and attendant effects on amount of standing timber stocks, are evident in the scenario outcomes. For example, increasing the timber yields 15% in regenerated stands in the future (Scenario B1), compared to the EO baseline, decreases the inventory before 2025 below baseline projections. Because of perfect foresight, the model can improve the total financial return for landowners by harvesting earlier in the projection period, in anticipation of higher growing stock inventory levels later due to increased investment.

Conversely, in FASOM-GHG, decreasing the timber yields for regenerated stands (Scenario B2) increases the volume of private standing timber relative to EO baseline projections until the period 2030, and then they drop below the baseline level. In this case, the model's foresight anticipates higher timber prices in the future with less standing timber inventory, and postpones some timber harvest until then.

This timing effect is more pronounced in the restricted investment scenario (Scenario C2), with standing timber volumes notably higher than under all alternative EO scenarios before 2045 (Fig. 3). However, timber growing stock under the restricted investment scenario then drops and diverges over time from the EO baseline. In addition, cumulative timber harvest levels over the entire projection period are materially lower than the EO baseline scenario (Table 1).

Although previous studies investigating the link between climate change and the forest sector have focused

on various economic and biological impacts of global climate change, there are some common themes. One earlier finding that is consistent with the FASOM-GHG model is that timber yield increases result in higher standing timber volumes. Alig et al. (2002) and Perez-Garcia et al. (2002) find that increasing timber yields increases standing timber volume over 100- and 40-yr projections, respectively.

Projected outcomes pertaining to the standing timber stocks in response to different forms of forest investment highlight important differences between financial and biological change to timberland management. Results from the FASOM-GHG model indicate that changes to standing volume accumulation over the projection period are more sensitive to timber yield variation than changes in costs for forest establishment and timber management. When timber yields are increased by 15% (Scenario B1), the projected timber volume in 2100 is 14% higher than that for a 50% reduction in forest establishment and timber management costs (Scenario A1).

However, the difference in standing timber volume due to biological and financial changes does not arise until period 2040. Before then, the difference between amounts of standing timber stocks for the yield (Scenario Set B) and cost-related (Scenario Set A) scenarios is less than 1%. Larger differences arise after 2045, given the lag in effects when timber stands are regenerated and appreciable timber volumes accumulate for such stands. Because changing the timber growth rate in timberland stands or the costs to establish and manage new stands does not have a large impact in the first 40 yr, from a policy perspective, the timing of carbon storage is also important in addition to the level of storage. Neither increases in regenerated timber yield or financial incentive have an immediate impact on the amount of standing timber volumes.

These results point to the importance, in the long run, of improvements to timber yields, versus subsidies to timberland establishment and management costs, to store more forest carbon through increased amounts of standing timber stocks. Even if increasing amounts of standing timber volumes depressed stumpage prices, the increased levels of growth in regenerated stands would promote volume accumulation throughout the projection. The model with perfect foresight will increase harvests in advance of anticipated increases in investment and inventory levels, so as to maximize the discounted net value of timber harvests. This results in standing timber volume or inventory levels being the highest at the end of the projection for scenarios with timber yield increases. In contrast, there are scenarios that reduce harvest and boost inventory levels in the initial periods, such as decreased timber yield for regenerated stands and a restriction on forest investment that eliminates tree planting.

If timber inventory levels are to increase monotonically throughout the projection period (out to 2100), then increased forest investment is required to produce regenerated timber yields that are at least 35% larger than baseline levels. Technological improvements, such

as improvement of genetic material, may play a role in any such yield boosts (e.g., Alig et al., 1999b), but also could affect land prices and lead to some conversion of forests to agricultural use.

At the other extreme, if no active investment in timber growing takes place (i.e., all natural regeneration representing reduced forest investment) (Scenario C2), then the timber inventory level by 2100 could be 17% lower than the base case. The aggregate inventory reduction would be particularly large in the South, which has a disproportionate amount of planted stands compared to other regions.

Although changing the timber yield levels has the greatest long-run impact to inventory levels, there is also a significant level of uncertainty. Little is currently known about the response on the stand level to global climate change (Burton et al., 1995), prompting sensitivity analyses of effects on timber yields (e.g., McCarl et al., 2000). Increasing the level of management, specifically on NIPF land, has the potential to increase levels of growth (Alig et al., 1999a). Intensification of forest management is sometimes viewed as the adoption of a complex regime of practices such as site preparation, planting, competition control, precommercial thinning, and so on. In practice, however, intensive management may involve nothing more than ensuring prompt and adequate regeneration after harvest or adjusting the form of partial removals to favor more rapid growth of residual trees. The effect of more intensive management, whatever its specific form, is to raise rates of forest growth and expand inventories on the available timberland base. Other ecosystem services that are related to the rate of growth and extent of inventory (e.g., CO₂ uptake, certain types of wildlife habitat, or visual amenities) may be enhanced as well. There are also potential gains in forest growth from elevated levels of CO₂ in the atmosphere. However, such estimates of increased level of growth from rising levels of CO₂ are variable (Joyce and Nungesser, 2000). Additional aspects of global climate change make the potential for increased levels of stand growth uncertain. The lag effect between global climate change and biological response adds to this uncertainty (Alig, 2003). Also, the possibility of increasing temperature and decreasing precipitation is also a factor that could reduce forest growth projections.

CONCLUSIONS

Our results demonstrate the importance of considering the joint nature of timber production and carbon storage, as timber markets dictate what carbon from private timberlands will be stored in forest ecosystems and wood products. Factors causing the largest short-term changes in total carbon storage are actions affecting the existing timber inventories, such as deforestation. For the longer term, which is approximately more than 20 or 30 yr in the future, increasing yields of regenerated stands can potentially provide more additional forest carbon storage in the United States than our simulated reductions in forest establishment and

timber management costs. Private timberlands in the United States have considerable potential for additional wood production and expanding carbon storage, but the amounts can vary notably over the next 100 yr and are subject to market-based adjustments reflecting global supply and demand conditions.

Our results point to the suite of biophysical–ecological, economic, and social factors that affect the amount and cost of carbon stored in forests. In addition to jointness in production for carbon and timber volumes, some factors interact, such as the ecological and economic factors that affect forest type transitions (e.g., Alig and Butler, 2004). Ecological successional trends can be altered by private timber harvest and regeneration that are driven by economic factors. Transitions among forest types could also be affected if owners recognize opportunity costs of storing carbon in forest ecosystems. Accounting for what happens across ownerships can be important, too, in that social differences in how forests are managed are reflected in the significantly lower timber harvest rates on federal timberlands. This may allow substantial buildups in standing timber volumes and carbon storage on such public timberlands (Alig et al., 2006; Smith and Heath, 2004), but also affect opportunity costs and carbon markets involving private forests.

One future research area pertains to simulation of carbon markets involving forests. This would include examining optimal mixtures of forest- and wood product-based carbon, both across time and space (e.g., regions). Although most attention in carbon storage analyses has been directed at afforestation and plantations, a broader policy viewpoint should include fate of carbon in harvested wood products and how to prolong lives of products in an efficient manner. The availability of many types of substitutable products and many sources of supply for any given forest product act to reduce the price impacts of supply shifts in forest products markets. Demand for timber products will also continue to grow. The United States has fairly stable per capita consumption of wood and paper products, at one of the highest levels in the world. Storage of carbon in wood and paper products is substantial, as in 1990 approximately 145 Tg of carbon, or 11% of the level of U.S. emissions, was harvested and removed from forests for products (Skog and Nicholson, 2000).

Given the joint production nature of forest ecosystems, carbon-related policies have the potential to usefully augment existing or future forest policies, and can have a positive effect on forest ecosystem stewardship. However, it is important to recognize the potential value of integrating carbon-related policies with others, such as enhancing biodiversity. Forests produce multiple goods and services, and climate change strategies can affect biodiversity and other environmental elements. For example, afforestation incentives could be targeted to jointly reduce atmospheric greenhouse gases, mitigate forest fragmentation (e.g., Alig et al., 2005), enhance biodiversity, and augment timber supplies, or some other combinations of those environmental attributes.

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REFERENCES

- Adams, D., R. Alig, B. McCarl, M. Callaway, and S. Winnett. 1997. The Forest and Agricultural Sector Optimization Model (FASOM): Model structure and applications. Res. Paper PNW-RP-495. USDA For. Serv., Pacific Northwest Res. Stn., Portland, OR.
- Adams, D., R.J. Alig, B.A. McCarl, J.M. Callaway, and S.M. Winnett. 1999. Minimum cost strategies for sequestering carbon in forests. *Land Econ.* 75(3):360–374.
- Alig, R., D. Adams, J. Chmelik, and P. Bettinger. 1999a. Private forest investment and long-run sustainable harvest volumes. *New For.* 17: 307–327.
- Alig, R., D. Adams, and B. McCarl. 1998. Ecological and economic impacts of forest policies: Interactions across forestry and agriculture. *Ecol. Econ.* 27:63–78.
- Alig, R., D. Adams, and B. McCarl. 2002. Projecting impacts of global climate change on the U.S. forest and agriculture sectors and carbon budgets. *For. Ecol. Manage.* 169:3–14.
- Alig, R., and B. Butler. 2004. Area changes for forest cover types in the United States: 1952 to 1997, with projections to 2050. Gen. Tech. Rep. PNW-613. USDA For. Serv., Pacific Northwest Res. Stn., Portland, OR.
- Alig, R., O. Krankina, A. Yost, and J. Kuzminykh. 2006. Forest carbon dynamics in the Pacific Northwest (USA) and the St. Petersburg region of Russia: Comparisons and policy implications. *Clim. Change* (in press).
- Alig, R., K. Lee, and R. Moulton. 1990. Likelihood of timber management on nonindustrial private forests: Evidence from research studies. Gen. Tech. Rep. SE-60. USDA For. Serv., Southern Res. Stn., Asheville, NC.
- Alig, R., D. Lewis, and J. Swenson. 2005. Is forest fragmentation driven by spatial configuration of the land quality? The case of western Oregon. *For. Ecol. Manage.* 217:266–274.
- Alig, R., T. Mills, and R. Shackelford. 1980. Most soil bank plantings in the South have been retained; Some need follow-up treatments. *South. J. Appl. For.* 4:60–64.
- Alig, R., A. Plantinga, S. Ahn, and J. Kline. 2003. Land use changes involving forestry in the United States: 1952 to 1997, with projections to 2050. Gen. Tech. Rep. PNW-587. USDA For. Serv., Pacific Northwest Res. Stn., Portland, OR.
- Alig, R.J. 2003. US landowner behavior, land use and land cover changes, and climate change mitigation. *Silva Fennica* 37(4):511–527.
- Alig, R.J., D.M. Adams, B.A. McCarl, and P. Ince. 1999b. Economic potential of short-rotation woody crops on agricultural land for pulp fiber production in the United States. *For. Prod. J.* 50(5): 67–74.
- Alig, R.J., J.D. Kline, and M. Lichtenstein. 2004. Urbanization on the U.S. landscape: Looking ahead in the 21st century. *Landsc. Urban Plan.* 69:219–234.
- Bair, L., and R. Alig. 2006. Regional cost information for private timberland conversion and management. USDA For. Serv., Pacific Northwest Res. Stn., Corvallis, OR (in press).
- Birdsey, R. 1992. Carbon storage and accumulation in United States forest ecosystems. Gen. Tech. Rep. WO-GTR-59. USDA For. Serv., Washington, DC.
- Birdsey, R., R. Alig, and D. Adams. 2000. Mitigation activities in the forest sector to reduce emissions and enhance sinks of greenhouse gases. In L.A. Joyce and R. Birdsey (ed.) *The impact of climate change on America's forests: A technical document supporting the 2000 USDA Forest Service RPA Assessment*. Gen. Tech. Rep. RMRS-GTR-59. USDA For. Serv., Rocky Mountain Res. Stn., Fort Collins, CO.
- Birdsey, R.A., and L.S. Heath. 1995. Carbon changes in U.S. forests. In L.A. Joyce (ed.) *Productivity of America's forests and climate change*. Gen. Tech. Rep. RM-271. USDA For. Serv., Rocky Mountain For. and Range Exp. Stn., Ft. Collins, CO.
- Burton, D.M., B.A. McCarl, D.M. Adams, J.M. Callaway, and S.M. Winnet. 1995. An exploratory study of the economic impacts of climate change on Southern forests: Preliminary results. p. 5–18. In J.E. de Steiguer (ed.) *Global change and forestry: Socioeconomic studies from the SOFEW 1994 meeting*. Gen. Tech. Rep. SE-GTR-92. USDA For. Serv., Southern Res. Stn., Asheville, NC.
- Hair, D., R.N. Sampson, and T.E. Hamilton. 1996. Summary: Forest management opportunities for increasing carbon storage. *For. Global Change* 2:237–254.
- Haynes, R. 2003. An analysis of the timber situation in the United States: 1952 to 2050. Gen. Tech. Rep. PNW-560. USDA For. Serv., Pacific Northwest Res. Stn., Portland, OR.
- Hoen, H.F., and B. Solberg. 1994. Potential and economic efficiency of carbon sequestration in forest biomass through silvicultural management. *Forest Sci.* 40(3):429–451.
- Intergovernmental Panel on Climate Change. 2000. Special report on land use, land use change, and forestry. Cambridge Press, Geneva.
- Joyce, L., and M. Nungesser. 2000. Ecosystem productivity and the impact of climate change. p. 45–66. In L.A. Joyce and R. Birdsey (ed.) *The impact of climate change on America's forests: A technical document supporting the 2000 USDA Forest Service RPA Assessment*. Gen. Tech. Rep. RMRS-GTR-59. USDA For. Serv., Rocky Mountain Res. Stn., Fort Collins, CO.
- Kline, J., B. Butler, and R. Alig. 2002. Tree planting in the South: Landowner behavior. *South. J. Appl. For.* 26(2):85–92.
- McCarl, B.A., D.M. Adams, R.J. Alig, and J. Chen. 2000. Effects of global climate change on the US forest sector: Response functions derived from a dynamic resource and market simulator. *Clim. Res.* 15(3):195–205.
- McCarl, B.A., D.M. Adams, B.C. Murray, and R.J. Alig. 2005. FASOMGHG conceptual structure and specifications: Documentation. Available at http://agecon2.tamu.edu/people/faculty/mccarlbce/papers/1212FASOMGHG_doc.pdf (verified 28 Feb. 2006). Texas A&M Univ., Lubbock.
- Murray, B. 2004. Overview of agricultural and forestry GHG offsets on the U.S. landscape. *Choices: The Magazine of Food, Farm, and Resource Issues*, Fall. p. 12–15.
- Perez Garcia, J., L.A. Joyce, A.D. McGuire, and X. Xiao. 2002. Impacts of climate change on the global forest sector. *Clim. Change* 54:439–461.
- Plantinga, A.J., and R.A. Birdsey. 1993. Carbon fluxes resulting from U.S. private timberland management. *Clim. Change* 23:37–53.
- Skog, K., and G.A. Nicholson. 2000. Carbon sequestration in wood and paper products. In L.A. Joyce and R. Birdsey (ed.) *The impact of climate change on America's forests: A technical doc. supporting the 2000 USDA Forest Service RPA Assessment*. Gen. Tech. Rep. RMRS-GTR-59. USDA For. Serv., Rocky Mountain Res. Stn., Fort Collins, CO.
- Smith, J., and L. Heath. 2004. Carbon stocks and projections for public timberlands in the United States: 1952–2040. *Environ. Manage.* 33(4):433–442.